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Review article

Sensory Processing Sensitivity in the context of Environmental Sensitivity: A critical review and development of research agenda

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ABSTRACT

Sensory Processing Sensitivity (SPS) is a common, heritable and evolutionarily conserved trait describing inter-individual differences in sensitivity to both negative and positive environments. Despite societal interest in SPS, scientific knowledge is lagging behind. Here, we critically discuss how SPS relates to other theories, how to measure SPS, whether SPS is a continuous vs categorical trait, its relation to other temperament and personality traits, the underlying aetiology and neurobiological mechanisms, and relations to both typical and atypical development, including mental and sensory disorders. Drawing on the diverse expertise of the authors, we set an agenda for future research to stimulate the field. We conclude that SPS increases risk for stress-related problems in response to negative environments, but also provides greater benefit from positive and supportive experiences. The field requires more reliable and objective assessment of SPS, and deeper understanding of its mechanisms to differentiate it from other traits. Future research needs to target prevention of adverse effects associated with SPS, and exploitation of its positive potential to improve well-being and mental health.

1. Introduction

To survive and thrive on planet earth it is essential for all organisms to draw on environmental resources, such as food, protection from predators and social support. Animals and humans are programmed to perceive, process, react and adapt to specific social and physical elements of the environment, both positive and negative ones. Of interest, there are substantial inter-individual differences in sensitivity and responsiveness to the environment in animals and humans; some are much more sensitive and reactive compared to others (Belsky and Pluess, 2009; Ellis et al., 2011). Across populations, a continuum from low to

high sensitivity to the environment is observed. In recent years, Sensory Processing Sensitivity (SPS), which describes inter-individual differences in trait sensitivity to experiences, and which began as a barely known topic 20 years ago (Aron and Aron, 1997), has become a much discussed facet of *Environmental Sensitivity* theory (Pluess, 2015). In this review, we discuss the knowns and unknowns in relation to the current conceptualisation of SPS, highlight the relevance and impact of the construct, and describe perspectives for future cross-disciplinary research.

SPS is part of a family of theoretical frameworks on *Environmental Sensitivity*. *Environmental Sensitivity* is an umbrella term for theories

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explaining individual differences in the ability to register and process environmental stimuli (Pluess, 2015). These include the theories of *Differential Susceptibility* (Belsky, 1997; Belsky and Pluess, 2009), *Biological Sensitivity to Context* (Ellis and Boyce, 2011), and *Sensory Processing Sensitivity* (Aron and Aron, 1997), the topic of the present review. All these theories state that individuals differ in their sensitivity to both aversive as well as supportive environments. Unique to *Sensory Processing Sensitivity* is that it proposes an underlying phenotypic (temperament) trait characterised by greater depth of information processing, increased emotional reactivity and empathy, greater awareness of environmental subtleties, and ease of overstimulation (Aron et al., 2012; Homberg et al., 2016). Early studies estimate that about 15–20% of the population can be considered high on the SPS trait (Aron and Aron, 1997). The first measure to assess SPS, the Highly Sensitive Person (HSP) Scale, is a 27-item self-report questionnaire of positive and negative cognitive and emotional responses to various environmental stimuli including caffeine, art, loud noises, smells and fabrics.

SPS is related to other temperament and personality traits reflecting sensitivity to environments. For example, traits such as introversion (or low extraversion), neuroticism (or irritability/ negative emotionality), and openness to experience have been associated with increased reactivity to environmental influences (Asscher et al., 2016; Hentges et al., 2015; Pluess et al., 2010). Furthermore, the Behavioural Inhibition System (BIS) and the Behavioural Activation System (BAS) (Gray, 1982), which describe the extent of pausing activity for the processing of conflicting information (BIS) and the urge to approach and satisfy needs (BAS), have been related to heightened sensitivity to negative and positive environmental stimuli, respectively. Nonetheless, analyses show that SPS is distinctive from these traits (Pluess et al., 2017).

Recent findings suggest that SPS is moderately heritable (Assary et al., 2019). Further, research has revealed associations between SPS and cognitive, sensory and emotional information processing in the brain (Acevedo et al., 2014, 2018; Acevedo et al., 2017; Jagiellowicz et al., 2016). This points towards a biological foundation for the SPS construct.

SPS is conceptualised as a temperament trait, and not a disorder. However, in adverse childhood environments, individuals with high SPS scores may shift from typical to atypical development, with a negative impact on well-being, and higher risk for behavioural problems and psychopathologies in childhood and adulthood (Aron et al., 2005; Booth et al., 2015; Liss et al., 2005). Conversely, individuals high on SPS exposed to positive events in life may flourish and perform exceptionally well, for example showing more positive mood and intervention responsivity (Pluess and Boniwell, 2015; Slagt et al., 2017), a result with important implications for policy makers and practitioners (Assary and Pluess, 2017).

Despite the above described insights from SPS research, several shortcomings remain. SPS brings advantages in terms of capturing a global phenotype through questionnaire-based and behavioural/observational assessment, its weaker point is that biological research on the aetiology and mechanisms underlying SPS is still in its infancy. How the so-far identified neural processes interact and shape sensitivity to the environment is not well understood yet. What is more, the relationship of SPS to existing personality and temperament constructs reflecting sensitivity to environments needs to be further clarified conceptually and empirically. Lastly, sensory sensitivities are also observed in mental disorders, but the relevance of SPS to seemingly related disorders and well-being needs to be further studied. Finally, more work is needed on interventions to foster the potential of high SPS individuals and prevent negative consequences.

1.1. Importance of studying SPS

From a theoretical point of view, studying SPS is important for deepening our understanding of a fundamental aspect of inter-individual differences in sensitivity to the environment, observed in

humans and animals (Aron and Aron, 1997; Homberg et al., 2016). Interestingly, recently SPS has been discussed also in the context of anthropological studies (Rappaport and Corbally, 2018). SPS also has implications for health, education and work: SPS is thought to be a significant factor impacting well-being, quality of life, and also functional difficulties (Aron et al., 2012). Thus, it needs to be studied rigorously and with respect to both basic and applied processes to improve well-being and life satisfaction, and preserve human capital, while preventing adverse effects and impairment among highly sensitive populations. From a societal impact perspective, SPS has gained substantial popularity in the public and media, with programmes being developed and professionals trained to coach and support highly sensitive employees, leaders, parents and children (e.g. <https://hsperson.com/resources/coaches/>). However, basic, translational and applied scientific research on SPS is lagging behind, creating an imbalance between the need for information from society and the scientific knowledge collected so far. This easily leads to misinterpretations of what SPS is, and comes with risk for misinformation and potentially even harm to the public, and neglects the societal responsibility of science.

1.2. Aim of review

The aim of this paper is to address the above shortcomings by critically discussing the state-of-the-art regarding scientific insights on SPS in a narrative review, and stimulating the field by proposing a future research agenda. We review the origins of the *Sensory Processing Sensitivity* framework and how it relates to other frameworks of *Environmental Sensitivity* (Section 2), how to measure SPS (Section 3), whether empirical evidence supports a dimensional or categorical conceptualisation of SPS (Section 4), the relationship of SPS to other temperament and personality traits (Section 5), what the underlying biological bases of SPS are (Section 6), and the relevance of SPS to mental health and intervention (Section 7). We have included all studies focusing on SPS directly, published in indexed journals included in PubMed and Scopus until September 2018, allowing a complete, exhaustive summary of the current literature on SPS and related field. We advocate that some speculation is required to set a comprehensive future research framework in which transdisciplinary approaches will be central. This review borrows from team science principles (Utzerath and Fernández, 2017) to bring together several authors with diverse areas of expertise to address the increasing complexity in science, requiring increased interdependency and specialisation in order to create more coherent research efforts. This allows the current review to take a broader perspective as well as updated view compared to the previous review on SPS (Aron et al., 2012), for instance through a greater focus on neuroscience and biobehavioural mechanisms, including animal work and the operationalisation of core components of SPS, as well as links to mental health and intervention.

2. SPS and theories of *Environmental Sensitivity*

2.1. Integrating different theories of *Environmental Sensitivity*

Since the late 1990s, several theoretical contributions, which have been developed independently from each other, have investigated such individual differences in sensitivity to environments. Initially, sensitivity was primarily seen as a vulnerability. The *Diathesis-Stress* model, also *Dual-Risk* model, proposes that individuals characterised by individual risk factors (e.g. specific gene allele variant, or higher emotional reactivity) have a predisposition to suffer the negative consequences of environmental adversities more than others (Ellis et al., 2011; Monroe and Simons, 1991; Pluess and Belsky, 2009). However, subsequent theories proposed that more sensitive individuals experience stronger effects and responsivity to both negative and positive environmental conditions and stimuli. These theories include

Differential Susceptibility (Belsky, 1997; Belsky and Pluess, 2009), *Biological Sensitivity to Context* (Boyce and Ellis, 2005), and *Sensory Processing Sensitivity* (Aron, 2002; Aron and Aron, 1997).

Differential Susceptibility, which has roots in developmental psychology, poses that highly sensitive individuals have a higher susceptibility to the environment, and assumes an evolutionary perspective by positing that individual differences in sensitivity (low and high sensitivity) represent two alternative developmental strategies (low and high plasticity and adaptation) maintained by natural selection to increase diversity and fitness of the species (Belsky et al., 1998; Belsky and Pluess, 2009). More recently, the *Vantage Sensitivity* theory has been put forward, which concerns individual differences in response to positive stimuli, such as supportive psychological interventions without making claims about the potential response to adverse experiences (de Villiers et al., 2018; Pluess and Belsky, 2015). In essence, *Differential Susceptibility* integrates the *Diathesis-Stress* and *Vantage Sensitivity* frameworks, by suggesting responsiveness to both positive and negative environments. *Differential Susceptibility* puts emphasis on phenotypic temperament characteristics, endophenotypic attributes and genetic variants that may act as plasticity factors that make people more malleable to environmental influences (Belsky et al., 1998; Belsky and Pluess, 2009).

In contrast, *Biological Sensitivity to Context* focuses specifically on physiological differences in reactivity (e.g. arterial pressure, cortisol production, immune reactivity) to environmental stimuli (Boyce and Ellis, 2005). It is defined as neurobiological susceptibility to cost-inflicting as well as benefit-conferring environments, and operationalised as an endophenotype reflecting heightened reactivity in one or more stress response systems (Boyce and Ellis, 2005). In other words, stress response systems increase susceptibility to negative environments, but also to resources and support (e.g. cooperative information, social opportunities) (Ellis et al., 2011; Pluess and Belsky, 2009). Compared to *Differential Susceptibility*, which emphasises that differences in sensitivity are genetically determined and a result of bet-hedging against uncertain futures, *Biological Sensitivity to Context* emphasises the role of early environmental pressures in shaping sensitivity as it is based on the evolutionary notion of conditional adaptation, as high sensitivity is thought to develop in response to both extreme negative or positive environments (Del Giudice et al., 2011; Ellis and Boyce, 2011).

The *Sensory Processing Sensitivity* framework has been developed based on extensive review of the animal literature, and informed by temperament and personality theories on behavioural inhibition, shyness, and introversion in children and adults (Aron, 2002; Aron and Aron, 1997). *Sensory Processing Sensitivity* emphasises that sensitivity can be captured in a phenotypic temperament or personality trait, characterised by greater depth of information processing, increased emotional reactivity and empathy, greater awareness of environmental subtleties, and ease of overstimulation, thought to be driven by a more sensitive central nervous system (Aron et al., 2012; Homberg et al., 2016). Environments in the context of *Sensory Processing Sensitivity* are broadly defined and include any salient conditioned or unconditioned internal or external stimuli, including physical environments (e.g. food, caffeine intake), social environments (e.g. childhood experiences, other people's moods, crowds), sensory environments (e.g. auditory, visual, tactile, olfactory), and internal events (e.g. thoughts, feelings, bodily sensations such as hunger, pain). Recently SPS has been discussed also in the context of anthropological studies (Rappaport and Corbally, 2018).

The described frameworks have recently been integrated within the broader *Environmental Sensitivity* meta-framework (Pluess, 2015), displayed in Fig. 1. Each of these frameworks on *Environmental Sensitivity* provides a unique contribution to the study of individual differences in response to the environment. The frameworks agree that individuals differ in sensitivity to environments, and that only a minority of the population are highly sensitive, as if a minority is sensitive this holds an evolutionary advantage. Benefits of sensitivity are frequency-dependent in that sensitivity is advantageous when rare but disadvantageous when

common (Aron and Aron, 1997; Belsky and Pluess, 2009; Jagiellowicz et al., 2012; Kagan, 2002; Suomi, 1997; Wolf et al., 2008). In essence, *Differential Susceptibility* proposes a mechanism (that is sensitivity to positive and negative environments), which is also underlying the *Biological Sensitivity to Context* and *Sensory Processing Sensitivity* frameworks. Unique to *Sensory Processing Sensitivity* is that it is the first framework to propose and develop a psychometric tool that captures sensitivity to environments directly as a phenotypic trait in adults and children (see Section 3), with important theoretical and applied implications for the study of individual differences in response to the environment.

2.2. Evidence for SPS as a marker of Environmental Sensitivity

Three observational studies were more in line with SPS acting as a vulnerability factor, in line with *Diathesis Stress* rather than *Differential Susceptibility*. An early study on SPS and the quality of the environment found an interaction between parenting environment and SPS, such that high SPS adults reporting having had an unhappy childhood scored higher on negative emotionality and social introversion, whereas high SPS adults reporting a happy childhood differed little from the larger population of non-highly sensitive adults on these traits (Aron and Aron, 1997). Furthermore, in adults SPS was shown to moderate the effect of parental care on depression symptoms (Liss et al., 2005). Individuals scoring high on SPS reported the highest depression scores when parental care was low, while depression scores were unrelated to SPS when parental quality was high (Liss et al., 2005). A study on life satisfaction in adults showed that while individuals high in SPS reported lower life satisfaction when childhood experiences were particularly negative, no evidence was found for differential effects to positive experiences (Booth et al., 2015).

The other studies were more in line with *Differential Susceptibility*. A paper by Aron et al (2005) for the first time reported a crossover interaction in three studies involving adults. Individuals high in SPS who reported a troubled childhood scored especially high on negative affect measures, but individuals high in SPS without such childhoods scored especially low on negative affect measures. This provided evidence that high SPS scores are linked to benefitting more from positive experience, in line with *Differential Susceptibility*. Furthermore, a six-month longitudinal study assessing SPS in kindergarten children, reported that SPS interacted with changes in positive and negative parenting in predicting externalising behavioural problems (Slagt et al., 2017). Children scoring high on SPS were most responsive to changes in parenting behaviour in both directions, predicting increasing externalising problems when parenting became more negative, as well as predicting decreasing externalising problems when parenting improved, supporting *Differential Susceptibility*.

Recently, laboratory studies have provided additional evidence that individuals high in SPS indeed show heightened responsiveness to negative and positive experiences. Adults high in SPS who were exposed to a positive mood induction video-clip, have been shown to have greater changes in positive affect compared to those reporting low sensitivity (Lionetti et al., 2018). Furthermore, adults scoring high on SPS have been shown to be more willing to trade off their privacy when viewing terrorism-related pictures compared to high SPS individuals viewing neutral pictures, whereas such a difference was not observed in individuals with low SPS scores (Rubaltelli et al., 2018). This suggests that individuals high in SPS may be more sensitive to terrorism-related media and community themes.

Two intervention studies have provided evidence for greater intervention responsiveness related to higher SPS, in line with *Vantage Sensitivity*. An intervention study in adolescent girls, found that girls high (versus low) in SPS responded more favourably to a school-based resiliency programme based in concepts of cognitive-behavioural therapy and positive psychology techniques (Pluess and Boniwell, 2015). Specifically, girls scoring high on SPS showed a significant

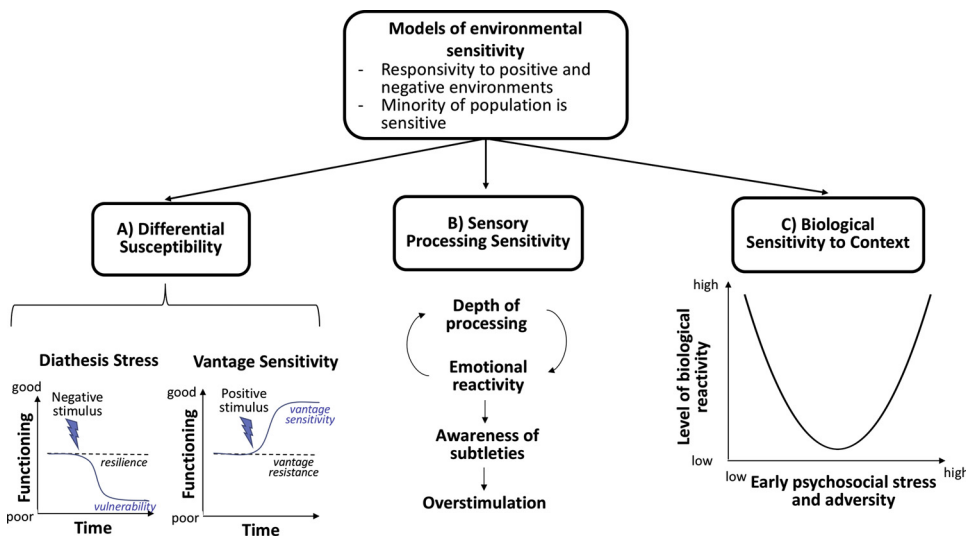


Fig. 1. Models of Environmental Sensitivity.

A) *Diathesis stress*: Emphasises vulnerability or resilience in response to adverse environments. *Vantage Sensitivity*: emphasises vantage resistance or vantage sensitivity in response to positive environments, without making claims about response to negative environments. *Differential Susceptibility*: combines vantage sensitivity and diathesis stress models: Individuals are differentially susceptible not only to negative environments, but also to beneficial effects of positive environments. Emphasises moderation of environmental influences by genetics, temperament and endophenotypes.

B) *Sensory Processing Sensitivity*: Sensitivity captured in a behavioural (temperament) trait, hypothesised to reflect increased depth of processing, awareness of subtleties, emotional reactivity and ease of overstimulation. We hypothesise that greater depth of processing, in interaction with emotional reactivity, is the

core underlying component, leading to greater awareness of subtleties and ease of overstimulation.

C) *Biological Sensitivity to Context*: Emphasis on sensitivity as a biological property indexed by heightened reactivity in stress response system. Hypothesises biological reactivity to emerge from both highly stressful and highly protected early social environments.

Models A), B) and C) all describe individual differences in sensitivity to both negative and positive environments, and all hypothesise heightened sensitivity or reactivity to be present in a minority of the population, for evolutionary reasons.

reduction in depression symptoms, which was evident at six and 12-month follow ups, whereas girls low in sensitivity did not show any significant change. These findings of heightened responsivity to positive experiences in individuals scoring high in SPS have recently been replicated in a large randomized control trial ($N = 2024$) testing the efficacy of a school-based anti-bullying intervention (Nocentini et al., 2018). In line with expectations, the results of this study showed that the intervention significantly decreased victimisation and bullying across the entire sample. However, a more in-depth analysis of interaction effects showed that intervention effects were driven primarily by children scoring high in SPS. Conversely, for children scoring low on SPS, no significant effect was reported. Furthermore, SPS has been shown to moderate the impact of early negative parenting styles on behavioural problems, and of positive parenting styles on social competence at age three and six (Lionetti et al., 2019), suggesting that is able to capture behavioural traits relating to sensitivity toward both positive and negative environmental stimuli. Overall, these findings provide evidence that SPS, as assessed by questionnaire or behavioural observation, is related to heightened responsivity to negative as well as positive environments.

2.3. Future directions

Future studies should expand research on SPS as a sensitivity marker to both positive and negative environments. Going beyond a correlational approach, more research is needed that manipulates the positive or negative environmental variable in more controlled laboratory contexts or within intervention studies. Furthermore, testing *Differential Susceptibility* in SPS in the context of daily life is important, to capture ecologically valid assessments of micro stressors (e.g. daily hassles and daily uplifts) and macro stressors (e.g. major positive and negative life events such as life transitions). Ecological Momentary Assessments, which involve assessing the participant in real time in their natural environment, would be a particularly useful tool to examine whether high SPS individuals are more responsive to positive and negative events throughout their daily life. Future studies which test the interaction between SPS and environmental events/quality ranging from low to high will benefit from conducting more sophisticated analysis as the Regions of Significance analyses (Roisman et al., 2012), as a superior method for testing *Differential Susceptibility* than the

simple slopes method, as it is able to distinguish where the significance of crossover interactions lie. Another approach involves the reparametrized equation approach (Belsky et al., 2013; Widaman et al., 2012), which allows one to compare different Environmental Sensitivity models based on crossover intersection points and associated confidence intervals. Furthermore, studies have predominantly used cross-sectional study designs. Longitudinal study designs would allow a more in-depth analysis of causation and of differences at a within-person level, and the study of short- and long-term dynamic changes in response to environments. One pertinent question is whether SPS is a stable trait across development, or whether certain experiences lead to changes in levels of SPS. Lastly, biological underpinnings of *Differential Susceptibility* in SPS is only beginning to be unravelled (Section 6), and it remains unclear whether the same biological systems that support responsivity to negative environments also support responsivity to positive environments in high SPS individuals. We also need better understanding how the core hypothesised features in SPS relate to one another (depth of processing, emotional reactivity and empathy, sensitivity to subtleties, overstimulation), and increase aetiological and neural understanding underlying the Sensory Processing Sensitivity framework. We make suggestions as to how this can be achieved in Section 6, and in Fig. 1.

3. Assessment of SPS

3.1. SPS scales: the Highly Sensitive Person (HSP) and Highly Sensitive Child (HSC) scales

The first measure for assessing SPS, namely the Highly Sensitive Person (HSP) scale (Aron and Aron, 1997), developed alongside the theoretical framework of *Sensory Processing Sensitivity*, was the result of an exploratory and empirical study of what is meant when the term sensitive is used by clinicians and by the public. Elaine Aron and Arthur Aron conducted a series of in-depth qualitative interviews with 39 adults who self-identified as “highly sensitive”, “introverted”, or “easily overwhelmed by stimuli” (Aron and Aron, 1997). The first 60-item HSP Scale was based on these interviews and included statements regarding being highly conscientious, startling easily, having a rich inner life, and being more sensitive to pain, all considered markers of increased sensitivity. This contributed to defining the construct of SPS as referring to

a broader sensory processing of information captured by a variety of indicators, rather than simply sensitivity toward sensory stimuli. The questionnaire was tested on a broader sample including 604 undergraduate psychology students and 301 individuals from a community sample, resulting in the self-report 27-item HSP scale, currently used for assessing SPS in adults (Aron and Aron, 1997). The psychometric properties and validity of the 27-item HSP scale, as well as shorter version (Acevedo et al., 2014; Lionetti et al., 2018; Pluess et al., 2017; Rubaltelli et al., 2018), have subsequently been validated in multiple studies (see below).

Building on the HSP scale for adults, the recent Highly Sensitive Child (HSC) Scale, a 12-item self-report measure of SPS in children as young as 8 years of age has been developed (Pluess et al., 2017). The scale includes items such as “I find it unpleasant to have a lot going on at once” and “Some music can make me really happy”. The HSC scale has also been used in a parent-report format in order to assess sensitivity in kindergarten children (Slagt et al., 2017), based on the same items from the HSC scale but rephrased so that it is the parent reporting on the child’s behaviour. The analysis of the factorial structure of the scale indicated that the HSC scale has adequate internal consistency and good psychometric properties across independent samples (Pluess et al., 2017; Weyn et al., 2019). Its criterion validity has been confirmed by showing that children scoring high on this scale are more sensitive and responsive to the positive influence of psychological interventions (Nocentini et al., 2018; Pluess and Boniwell, 2015), as well as to both positive and negative parenting quality (Slagt et al., 2017).

There is also another 23-item parent-report questionnaire assessing SPS in children (Aron, 2002). This questionnaire includes items such as “My child is bothered by noisy places” or “My child seems very intuitive”, and has been used to examine its association with daily functioning in a Dutch-sample involving parents of children ages 3–16 (Boterberg and Warreyn, 2016). The items of this questionnaire partially overlap with the HSC questionnaire. However, this questionnaire scale has not yet been validated as to whether children scoring high on this measure are more sensitive to environmental influences and process information more deeply.

The HSP/HSC scales have been translated into several languages. Dutch (Weyn et al., 2019), Italian (Nocentini et al., 2017), German (Konrad and Herzberg, 2017; Tillmann et al., 2018), Turkish (Şengül-İnal and Sümer, 2017), Japanese (Kibe et al., 2018) and Icelandic (Þórarinsdóttir, 2018) versions are available, and the HSC partial measurement invariance has been confirmed across age, gender, and country based on Dutch and UK versions (Weyn et al., 2019). Both HSC and HSP scores tend to be normally distributed in the population (Booth et al., 2015; Pluess et al., 2017), although some authors have pointed out a slight trend towards a bimodal distribution (Aron et al., 2012; Lionetti et al., 2018).

Finally, the questionnaire-based assessment of SPS has been recently extended to the study of personality in animals. The Highly Sensitive Dog owner-report questionnaire has been developed for the assessment of a canine-SPS trait in domestic dogs (Braem et al., 2017). Animal models of SPS have also been developed (see Section 6).

3.2. SPS behaviour observation: the HSC rating-system

The HSC Rating-System provides a behavioural observation assessment of SPS in pre-schoolers aged 3–5 years (Lionetti et al., 2017). The development of the measure was guided by a theory-driven approach inspired by the theoretical definition of SPS in children (Aron, 2002) and by the definition of the broader construct of *Environmental Sensitivity* (Pluess, 2015). The rating system, applied to a series of laboratory episodes derived from the Laboratory Temperament Assessment Battery procedure traditionally used for the coding of temperament (Goldsmith et al., 1999), and coded by external observers trained on this method, has been found to capture children’s sensitivity to the rearing environment, moderating the impact of both positive and negative

parenting on positive and negative children’s outcomes (Lionetti et al., 2019). The validation of the HSC Rating-System is currently limited to an American middle-class population and to a single study. However, given that it provides a multi-modal, and a more objective behavioural measure, it promises to be a useful tool for future research on SPS in children. Proper administration and coding of behaviour observation is key as external observers may misinterpret a child’s signals and certainly may lack access to the child’s inner world.

3.3. Components of HSP and HSC scales, and HSC rating-system

Initial factor analyses on the HSP scale suggested a unitary sensitivity factor captured by a variety of items (Aron and Aron, 1997). However, subsequent factor analyses exploring alternative solutions found convergence for different components (Smolewska et al., 2006). In recent years, they have been often adopted in SPS studies as a way for describing features characterising the SPS trait.

The most extensively psychometrically supported solution across children and adults (Pluess et al., 2017; Smolewska et al., 2006) includes the following components: 1) Low Sensory Threshold (LST, i.e. sensitivity to subtle external stimuli), 2) Ease of Excitation (EOE, i.e. being easily overwhelmed by internal and external stimuli), and 3) Aesthetic Sensitivity (AES, i.e. openness for, and pleasure of, aesthetic experiences and positive stimuli). The three sensitivity components of LST, EOE and AES have been found to relate differentially to affect variables. More specifically, EOE and LST were both found to be associated with a moderate effect size with self-reported negative emotionality, anxiety and depression (Liss et al., 2005), and LST, but not EOE, has been reported to correlate with self-rated sensory discomfort (Weyn et al., 2019). Conversely, AES was reported to be associated with positive emotionality such as positive affect and self-esteem, but not with negative emotions, both in adulthood and childhood (Pluess et al., 2017; add: Sobocko and Zelenski, 2015). Importantly however, the LST, EOE and AES subscales were not designed, but emerged when analysing the scale, further their biological validity is unclear, and it is not clear what the components measure or mean when taken separately.

Recently, reconciling the apparently contradictory views of the existence of a unique, general, SPS factor or different components of sensitivity, psychometric data across childhood, adolescence and adulthood, provided evidence in support of a bifactor solution. This solution includes a general SPS factor and allows recognition of the multidimensionality of the HSC and HSP scales, as represented by the three sensitivity components of LST, EOE and AES (Lionetti et al., 2018; Pluess et al., 2017). These results are consistent with findings identifying the summary score of the HSP and HSC scales capturing an increased sensitivity to positive and negative stimuli (Slagt et al., 2017).

The 23-item parent-report HSP questionnaire for children (Aron, 2002; Boterberg and Warreyn, 2016) showed two factors: Overreaction to Stimuli, which comprised items associated with overstimulation, emotional intensity and sensory sensitivity (e.g. “My child is bothered by loud noises”) and Depth of Processing (e.g. “My child asks deep, thought-provoking questions”). Because this parent-report questionnaire includes additional (and partially distinct) items compared to the more extensively studied HSC scale for children (Nocentini et al., 2018; Pluess et al., 2017; Pluess and Boniwell, 2015; Slagt et al., 2017), this result may suggest that the inclusion of other items could allow one to capture specific SPS aspects not currently included in the HSC self-report questionnaire.

Finally, a one-factor solution emerged for the newly developed observational HSC Rating-system for pre-schoolers (Lionetti et al., 2019). This unique SPS factor correlated moderately and negatively with assertiveness (which captures the degree to which the child makes requests or demands, offers suggestions, or draws attention to him/herself), and moderately and positively with constraint (which pertains to regulatory aspects as inhibitory/effortful control), and all temperament factors together explained only half of SPS variance. Overall,

these results suggest that though SPS is associated with observed temperament to a moderate extent, it is not fully captured by other temperament factors (Dyson et al., 2012).

3.4. Future directions

More objective assessment procedures for SPS would be a very valuable alternative or addition to questionnaire-report. For infants and children, this could take the form of observational measures similar to the HSC Rating-system developed for pre-schoolers. From middle childhood and in adulthood, a semi-structured interview on SPS, which remains to be developed, would be valuable. Such an interview would provide a richer and more nuanced assessment of sensitivity as it includes observer-rated observational data based on the trained interviewer's judgments in interpreting responses (Trull et al., 1998). The assessment of SPS could also be made more objective by the addition of cognitive-, genetic- or bio-markers (see Section 6).

While the HSP and HSC scales have good psychometric properties and have been validated in multiple ways (also see below), the scales need to be validated and optimised further. First, behaviours such as pausing to check in novel situations or taking time to make decisions, cardinal characteristics of individuals high in SPS and associated with depth of processing, are not sufficiently covered in the HSP and HSC scales (Aron and Aron, 1997). The items coming the closest to capturing depth of processing are those relating to the AES component. Nonetheless, the SPS scale has been associated with activation of brain areas involved in greater depth of processing, such as greater activation in secondary perceptual processing brain areas, in fMRI studies (see Section 6), suggesting that the existing scale does already capture depth of processing. More research is needed to test the ability of the scale to capture the SPS construct fully, or whether the additional items on depth of information processing are needed.

Second, HSP/HSC scale items are mainly negatively phrased (with the exception with those on the AES component), and may therefore not adequately capture the experience of highly sensitive individuals without psychological problems. Indeed, many of the items on the HSC/HSC scales appear to describe negative consequences of greater depth of information processing (with the exception of the AES items). One of the authors of this manuscript (E. Aron) has developed a less negatively, and more neutrally worded version of the HSP scale, which is currently being validated (E. Aron, personal communication, July 8, 2018).

Lastly, regarding cultural differences, the analysis of the HSC scale invariance across cultures suggests that while the underlying structure of the scale is conceptualised similarly between Belgian and British people, and Belgian and British people attribute more or less the same meaning to the latent construct of the scale, the mean differences may not be comparable. That is, Belgians tend to score higher on some items (mainly to those belonging to the AES scale), a trend that has been reported also for Italian children (Nocentini et al., 2017). This suggests that some items may need to be adapted for cultural sensitivity, while retaining the pure assessment of SPS.

4. SPS as a category or continuum?

The literature on SPS suggests that roughly 20% of the population is assumed to be highly sensitive and 80% less sensitive (Aron et al., 2012). A popular metaphor is the Orchid-Dandelion metaphor, where *Dandelions* reflect the majority of the population (around 80%) who are less sensitive to the influence of either positive or negative environments, whereas *Orchids* (the remaining 20%) are more strongly affected by environmental adversity but also flourish more in positive environments (Boyce and Ellis, 2005). That 20% of the population is highly sensitive was first proposed by the theory on SPS as an analogy to the work on infant reactivity (or behavioural inhibition), as defined by Kagan (1994b). These researchers categorised infants into qualitative groups of infant reactivity, based on a theoretical framework concerning differences in the excitability of limbic structures, and applied this model to observational judgments of motor and crying reactions in infants (Kagan, 1994a). Taxometric analyses, which are expressly designed to distinguish taxa from dimensions (Ruscio and Ruscio, 2004), supported their theoretical framework, by showing that a minority (around 10%) of infants were highly reactive to visual, auditory and olfactory stimuli, with the remainder falling into a less reactive group (Woodward et al., 2000). Moreover, Kagan's work, empirical studies, and computer-based simulation on other temperamental traits related to sensitivity to environments in human and animals also provided support for the existence of individual traits associated with heightened sensitivity to the environment (e.g. behavioural inhibition), as well as putative sensitivity gene variants (see Section 6) with a relatively low population frequency of about 10–35% (Aron and Aron, 1997; Belsky and Pluess, 2009; Jagiellowicz et al., 2012; Kagan, 2002; Suomi, 1997; Wolf et al., 2008). This was also further supported in a Diploma thesis on SPS using taxometric analyses on the HSP scale in $N = 898$ individuals, which revealed a high sensitive taxonic group with a base rate of 15–20% (Borries, 2012); although this work was not replicated in a Master's thesis (Kroenung, 2015).

Overall, taxometric research across personality and psychopathology, has yielded dimensional results more often than taxonic ones, and there is a strong trend that newer studies reveal dimensional results (Haslam et al., 2012). This has been suggested to be primarily due to improvements in taxometric practice, rendering early influential taxonic findings spurious (Haslam et al., 2012). Hence, we expect similar findings to emerge for the HSP/HSC scales.

More recently, two studies have applied latent class analysis (a data-driven hypothesis-free method to test the structure of latent variables) to the HSC and HSP scales. The first study identified three SPS classes across four ethnically-diverse UK-based samples containing 8–19 year olds (total $N = 3581$), using the HSC scale: a low (25–35%), medium (41–47%) and high (20–35%) sensitive group (Pluess et al., 2017). These latent class findings were replicated in a study on multiple US adult samples ($N = 451$ and $N = 450$) using the HSP scale, which also revealed a three (rather than two) -class solution: 31% high sensitive, 40% medium, and 29% low sensitive (Lionetti et al., 2018). The authors labelled this third class *Tulips*, who are intermediate between *Orchids*

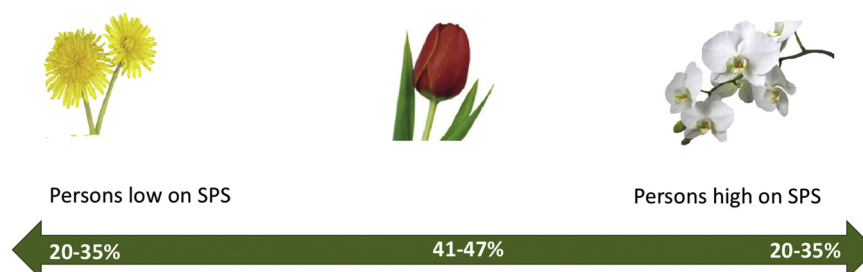


Fig. 2. SPS in across the population.

SPS is a continuous trait but people fall into three sensitivity groups along a sensitivity continuum.

and *Dandelions* in terms of their sensitivity scores (Fig. 2). Together, the studies suggested preliminary cut-off scores differentiating low, medium and high sensitive groups, which were relatively consistent across ages, but characterised by relatively low sensitivity and specificity (Lionetti et al., 2018; Pluess et al., 2017). In the adult study (Lionetti et al., 2018), the three-group categorisation was subsequently applied to an independent sample of 230 UK-based adults. This revealed that differences between the three detected sensitivity groups in response to a positive mood-induction task were more of quantitative rather than qualitative nature: *Orchid* individuals scored significantly higher in Neuroticism and emotional reactivity and lower in Extraversion than *Dandelions* and *Tulips*, with *Tulips* also significantly differing from *Dandelions* and scoring intermediate to *Dandelions* and *Orchids* (Lionetti et al., 2018). In both studies, the HSP/HSC scales were relatively normally distributed. Overall, these findings suggest that SPS is a continuously distributed trait but that people fall into three sensitivity groups along a sensitivity continuum.

4.1. Future directions

Whether SPS should be considered as a dimensional (also continuous, quantitative) or categorical (also taxonic, discrete, qualitative) trait is an important question. Dimensionality would suggest that individuals in the population differ merely quantitatively in level of SPS traits with normal variation from low to high (differences in degree). In contrast, categorisation would suggest that individuals in the population can be separated into non-arbitrary, qualitatively different sensitivity groups (differences in kind). Clarity about the categorical or dimensional nature of SPS has consequences for how SPS should be assessed, and for the selection of suitable research designs (Ruscio and Ruscio, 2004).

Overall, the more recent research on the HSP and HSC scales suggests that SPS is a continuous trait, along which individuals fall into different sensitivity classes. In terms of future work, taxometric analyses on the HSC/HSP scales would be a useful addition to the already conducted latent class analyses (Lionetti et al., 2018; Pluess et al., 2017), which would address the questions of distinguishing taxa from dimensions more directly (Ruscio and Ruscio, 2004).

5. SPS and Temperament/Personality traits

Aron and Aron (1997) introduced SPS as a trait related to, but distinct from other temperament and personality constructs. Being developed based on extensive review of the animal literature, it has been suggested that SPS may relate to a general trait of sensitivity to the environment, or meta-personality trait of contextual sensitivity, which structures (animal) personality differences through determining the degree to which individual behaviour is guided by environmental influence (Aron et al., 2012). In light of this, we discuss here SPS within the context of temperament and personality constructs.

5.1. Eysenck's personality theory

According to Eysenck (1967), individual differences in personality can be described in terms of two dimensions: introversion (vs extraversion) and neuroticism (vs emotional stability). Introversion relates to the optimal level of arousal at which an individual performs best: for those high in introversion, this level is way lower than for those high in extraversion. Neuroticism comprises proneness to distress and emotional instability. In a series of seven studies, Aron and Aron (1997) examined associations of SPS with introversion and neuroticism. They found low to moderate associations with introversion (Pearson's r median correlation around 0.29) and fairly high associations with neuroticism (median .54). As to introversion, qualitative research by Aron and Aron (1997) shows that not all highly sensitive individuals display the profile of being socially introverted.

5.2. Gray's reinforcement sensitivity theory

As an alternative to Eysenck's theory, Gray's Reinforcement Sensitivity Theory (RST: Gray, 1982) proposed that individual differences in the sensitivity of basic brain systems underlie individual differences in personality: the Behavioural Inhibition System (BIS), Behavioural Approach System (BAS), and Fight/Flight System (FFS). In the original version of the theory, the BIS was thought to mediate reactivity to conditioned punishment and frustrating non-reward, and to underlie negative emotions, in particular anxiety. The BAS was thought to be reactive to conditioned stimuli signalling reward or relief from punishment and underlie positive emotions. The FFS was thought to modulate responses to unconditioned aversive stimuli and to underlie fear and defensive aggression. In 2000, Gray and McNaughton (Gray and McNaughton, 2000) published a revision of the RST. In this revised RST, the BAS still functions as a reward system, and modulates responses to all appetitive stimuli (unconditioned as well as conditioned). Similarly, the FFS was assumed to modulate responses to all aversive stimuli and renamed to Flight, Fight and Freezing System (FFFS). The BIS was now thought to be activated by stimuli that activate both the BAS and FFFS, and responsible for the inhibition of ongoing behaviour in the service of conflict detection and resolution. According to Aron and Aron (1997), SPS is especially related to BIS functioning, given the 'pause-to-check' function of this system. Consistent with this assumption, Smolewska et al. (2006) reported a positive association of BIS sensitivity with SPS as a global construct, as well as with its three components. In the same study, BAS sensitivity was found to be largely unrelated to SPS. If narrower facets of BAS are differentiated, i.e. positive affect vs approach motivation in response to incentive cues, only the former showed a small significant association with SPS as a global construct and with the components of EOE and EAS. More recently, Pluess et al. (2017) examined the association of SPS with BIS and BAS sensitivity in two samples of children. They found significant positive correlations of both BIS and BAS sensitivity with SPS as a global construct, as well as with EOE and EAS components. Only BIS sensitivity was also positively correlated with the LST component.

5.3. Rothbart's temperament model

According to Rothbart et al. (Rothbart, 2011; Rothbart and Derryberry, 1981) temperament can be described as individual differences in emotional, motor, and attentional reactivity as measured by latency, intensity, recovery of response, and self-regulation processes that modulate reactivity (Rothbart, 2007). Temperamental reactivity refers to responses to change in the external and internal environment, measured in terms of the latency, duration and intensity of emotional, orienting and motor reactions. Self-regulation refers to processes that serve to modulate reactivity, especially processes of executive attention and effortful control. Depending on the developmental stage, three to five broad temperament domains are distinguished. Positive affectivity/extraversion reflects one's level of pleasurable engagement with the environment and the extent to which a person feels active, happy and enthusiastic; negative affectivity reflects subjective distress and an unpleasurable engagement with the environment; effortful control comprises processes that modulate reactivity, such as attentional control, inhibitory control and activation control. In some developmental stages, affiliative motivation (i.e. the desire for closeness with others) and/or orienting sensitivity/openness (i.e. automatic attention to both external sensory events and spontaneously occurring thoughts and images) are conceived as separate domains.

Evans and Rothbart (2008) examined the association of SPS components with temperament domains and facets of Rothbart's model in adults. For SPS, a two-factor conceptualization was used: one factor combined the EOE and LST components reported by Smolewska et al. (2006); the other was identical to the AES component. Similar findings have been reported in a sample of gifted young adults (Rinn et al.,

2018). In Evans and Rothbart's paper (2008), the combined EOE/LST component (called negative affect) of SPS was found to have a strong positive association with negative affectivity (particularly the facet of sensory discomfort), a moderate negative association with effortful control and a relatively low negative association with positive affectivity/extraversion. The AES component of SPS (called openness) was found to have a strong positive association with all facets of orienting sensitivity from Rothbart's model, and low to moderate positive associations with positive affectivity/extraversion and affiliative motivation. Sobocko and Zelenski (2015) replicated the positive associations between the negative affect component of SPS (EOE as well as LST) and negative reactivity in Rothbart's model. Bridges and Schendan (2019a) replicated the association between negative affect of the SPS (EOE, LST) and negative reactivity based on both Rothbart and colleagues' model of SPS and their adult temperament scale. Further, EOE and LST components of the SPS are moderately negatively correlated with Rothbart's extraversion/surgency (validating the association of SPS and introversion) but weakly positively correlated with Rothbart's orienting sensitivity, and all components of SPS are weakly negatively related to Rothbart's effortful control (consistent with less attentional filtering in SPS). Sobocko and Zelenski (2015) also replicated the positive associations between the AES component of SPS and positive affectivity/extraversion in Rothbart's model. Bridges and Schendan (2019a) also found the AES component of SPS to be positively associated with orienting sensitivity (defined using both the model and questionnaire of Rothbart et al.). Pluess et al. (2017) reported, in samples of 9–18 year olds, positive correlations of negative affectivity, positive affectivity and effortful control with SPS as a global construct as well as with EOE, LST and EAS (with the exception of the association of positive affectivity with LST, which was non-significant).

5.4. *Mc Crae and Costa's five-factor model of personality*

The five-factor model of personality (McCrae and Costa, 1994) comprises five broad personality domains, derived from natural language using a lexicographic approach. The domains include Extraversion, Neuroticism, Openness to experience, Agreeableness and Conscientiousness and each domain has a number of specific facets. As a global construct, SPS has been found to be positively associated with Neuroticism with a moderate effect size (Lionetti et al., 2018; Listou Grimen and Diseth, 2016; Pluess et al., 2017; Smolewska et al., 2006; Sobocko and Zelenski, 2015) and negatively associated with the domain of Extraversion (Lionetti et al., 2018; Listou Grimen and Diseth, 2016; Pluess et al., 2017; Smolewska et al., 2006; Sobocko and Zelenski, 2015). Also, in most studies SPS was found to be positively associated with Openness to experience (Bridges and Schendan, 2019a; Lionetti et al., 2018; Listou Grimen and Diseth, 2016; Pluess et al., 2017; Smolewska et al., 2006; Sobocko and Zelenski, 2015). Five studies examined associations of SPS as global construct with the domains of Agreeableness and Conscientiousness; in none of the studies, these associations were significant (Bridges and Schendan, 2019a; Lionetti et al., 2018; Pluess et al., 2017; Smolewska et al., 2006; Sobocko and Zelenski, 2015).

When the three dimensions of SPS are examined separately, a differentiated picture emerges. Across studies, both EOE and LST were found to have a positive association with Neuroticism (Ahadi and Basharpour, 2010; Bridges and Schendan, 2019a; Listou Grimen and Diseth, 2016; Pluess et al., 2017; Smolewska et al., 2006; Sobocko and Zelenski, 2015). Also, both EOE and LST were found to be inversely related to Extraversion; these associations were, however, generally weaker and less consistent across studies than those with Neuroticism. In one study, in 15–19 year olds, EOE was inversely related to Conscientiousness (Pluess et al., 2017). In undergraduates, one study found both EOE and LST inversely relate to Openness (Lionetti et al., 2018), while another study in a diverse adult sample found a weak positive relation for LST (Bridges and Schendan, 2019a). In another study, in

undergraduates, both EOE and LST were inversely related to Openness (Lionetti et al., 2018). AES was consistently found to be positively associated with Openness to experience (Ahadi and Basharpour, 2010; Bridges and Schendan, 2019a; Lionetti et al., 2018; Listou Grimen and Diseth, 2016; Smolewska et al., 2006; Sobocko and Zelenski, 2015). In three studies, AES was also positively related to Conscientiousness (Ahadi and Basharpour, 2010; Pluess et al., 2017; Sobocko and Zelenski, 2015) and in two studies AES was positively related to Neuroticism but much less so than to Openness in line with the greater relation between AES and positive than negative affect characteristics (Ahadi and Basharpour, 2010; Bridges and Schendan, 2019a; Lionetti et al., 2018). In most studies, none of the SPS components were found to be significantly associated with Agreeableness. As an exception, in Lionetti et al. (2018) and Bridges and Schendan (2019a), a positive association between AES and Agreeableness emerged, in relation to a shortened 12-item version of the HSP scale, while a weak negative relation was found for LST and Agreeableness.

Two unpublished pilot studies have moved beyond the predominant focus on the domain level of the five-factor model to a fine-grained examination of which five-factor subdomains (called facets) are specifically relevant for SPS. In the first pilot study, a community sample of 16 through 26 year olds (N = 421) completed both the HSP and the NEO-PI-3 scales (P. Bijttebier, personal communication, April 5, 2018), and both domain- and facet-level associations were examined. At domain level, SPS was found to be positively associated with higher Neuroticism and Openness, negatively associated with Extraversion, whereas no significant association was shown with Agreeableness and Conscientiousness. At facet level, however, a more nuanced picture emerged showing that some of the associations at domain-level were driven by associations among some but not all facets. Also, it became clear that non-significant associations at the domain level resulted from opposite patterns of associations for facets with the same domain. These preliminary findings suggest that in order to comprehensively grasp the set of personality facets that characterize high SPS individuals, a facet-level analysis is needed.

A second pilot study (P. Bijttebier, personal communication, April 5, 2018) was conducted in a sample of 13 professionals who registered for a training programme "HSP for Professionals". Prior to the training, they were asked to fill in the NEO-PI-3, which assesses the five-factor model, taking the perspective of a prototypical highly SPS individual. Mean raw scores were converted to stanines in order to identify domains and facets that pop up as 'low'/'very low' or 'high'/'very high' compared to population norms. At domain level, Neuroticism popped up as 'very high', Agreeableness and Openness as 'high' and Extraversion as 'low'. Interestingly, above or below average domain scores were found to be driven by above or below average scores on only part of the facets. Also, an average domain score was found to be driven by the fact that within that domain, some facets popped up as 'high', whereas others popped up as 'low' or scored average. These preliminary findings suggest that high SPS might be considered as a blend of personality facets across domains. This opens opportunities to further extend and refine the set of tools available for the assessment of SPS, more specifically by constructing a five-factor model-based SPS compound consisting of all the facets that pop up as 'high' or 'low' in prototypical high SPS individuals.

5.5. *SPS simultaneously related to multiple personality constructs*

In some studies, constructs from different personality theories are simultaneously related to SPS. For example, Smolewska et al. (2006) examined the relative contribution of Neuroticism and BIS sensitivity in predicting SPS (subscales). They found that both Neuroticism and BIS sensitivity positively predicted SPS as a global construct, as well as the SPS components EOE and LST. The associations with Neuroticism were remarkably stronger than those with BIS sensitivity. In addition, Neuroticism (but not BIS sensitivity) positively predicted AES, although

that association was lower in magnitude than the associations with the other two subscales and with SPS as a global construct. In two recent studies in child samples, multiple regression analyses were used to examine associations of BIS and BAS sensitivity, positive and negative emotionality/affectivity and effortful control with SPS as a global construct as well as the EOE, LST and AES components (Pluess et al., 2017). The multivariate models predicted 26 to 34% of the variance of the SPS global score, and 15 to 35% of the variance of the SPS components. In the first study, BIS sensitivity and Neuroticism emerged as significant predictors of SPS as a global construct, as well as of EOE. BIS sensitivity (but not Neuroticism) also predicted LST. BAS sensitivity, positive emotionality/affectivity and – albeit to a lesser extent – BIS sensitivity predicted AES. In the second study, BIS sensitivity was unrelated to SPS (subscales), but Neuroticism was found to positively predict SPS as global construct, as well as EOE and LST. In addition, BAS sensitivity was inversely related to LST. And finally, positive emotionality positively predicted both SPS as global construct and AES. Across the two studies, EOE and LST were most consistently predicted by BIS sensitivity and negative emotionality, whereas AES was predominantly predicted by BAS sensitivity and positive emotionality. Nonetheless, these different personality constructs at best explained a modest proportion of the variance of SPS, suggesting that SPS is not fully explained or captured by existing temperament and personality constructs (Pluess et al., 2017).

5.6. Future directions

As reviewed above, SPS shows small to moderate associations with existing temperament and personality traits, even when these are taken together, and also differs conceptually from these temperament and personality traits. There is therefore reasonably good evidence that SPS can be considered a distinct construct. Whether SPS reflects a more fundamental or meta-personality trait of sensitivity to environments remains a hypothesis.

Future research should furthermore continue to examine associations of SPS with traditional temperament and personality constructs, as this can aid the understanding of SPS based on what is already known regarding personality constructs. For example, normative data are available for the five-factor model, but are not (yet) available for SPS. One potential advice is to extend the above pilot research on associations between SPS and the five-factor model facets. Different approaches are informative here: (a) a facet-level analysis of associations between HSP or HSC scores and five-factor model traits; (b) a comparison of the five-factor model domain and facet scores of high SPS individuals to population norms in order to identify domains and facets on which these individuals' children score either high or low.

6. Biological basis of SPS

6.1. Genetic and environmental aetiologies

Understanding the aetiology of any complex trait requires a vast effort culminating research from large-scale genetic databases. This often starts with twin data research, whereby the heritability of a trait is estimated by comparing twin correlations between monozygotic twins (who share 100% of their genetic make-up) and dizygotic twins (who share approximately 50% of their additive genes). This classical twin design can give an estimate of the proportion of variance in a trait that is explained by genetic, shared environmental and non-shared environmental factors (Boomsma et al., 2002). While this method is useful for elucidating whether genes play a role in a given trait, it cannot specify which genetic variants are implicated in its ontogeny. For this, molecular genetic studies are needed to find associations between traits and specific variants. Candidate gene studies test for associations with genetic variants such as single nucleotide polymorphisms (SNPs) that have some known biological function, therefore a priori assumptions

are made about the relevance of the gene for the given trait. Genome wide association studies (GWAS) search for associations across the entire genome and thereby represent a data-driven approach to find significant genetic variants. GWAS require data from huge samples of the population to account for statistical obstacles such as multiple comparisons.

Only one twin study has been conducted assessing the heritability of SPS. This study estimated that 47% of variance in SPS, assessed using the HSC scale in a UK population-representative sample of adolescents, could be explained by genetic factors, with the remaining variance explained by non-shared environmental factors (Assary et al., 2019). Multivariate analyses revealed that genetic influences on the AES component were largely distinct from those underlying LST and EOE. This may reflect an underlying multi-dimensional biological model of sensitivity, and it opens up the possibility that genetic factors may contribute to the development of subgroups of high SPS individuals who in particular score high on either AES or LST/EOE. SPS correlated significantly with five-factor model Neuroticism ($r = 0.34$) and Extraversion ($r = -0.18$) (but not the other five-factor domains), and these correlations were largely explained by shared genetic influences. This suggests that the small to modest extent to which SPS shares phenotypic overlap with the other personality traits, is due to shared genes.

Only two molecular genetic studies of SPS have been conducted. The first study included 169 individuals and reported an association between SPS and the serotonin transporter-linked polymorphic region (5-HTTLPR) (Licht et al., 2011). 5-HTTLPR has been shown to increase sensitivity to environmental stimuli, specifically negative but also positive ones (Beevers et al., 2011; Homberg and Lesch, 2011; Pearson et al., 2016). High SPS was related to s/s homozygosity (Licht et al., 2011). However, results from this study should be interpreted with caution given that the association between SPS and the s-allele was quite small, and the study had a small sample size. The second molecular genetic study assessed the association between SPS and multiple candidate genes in the dopaminergic system in a sample of 480 college students (Chen et al., 2011). Ten polymorphisms were reported to show significant associations with SPS and were included in subsequent regression analyses, which revealed that these polymorphisms together explained as much as 15% of variance in SPS, with recent stressful life events explaining an additional 2%. Such large effect sizes are rather unusual in molecular genetic studies and require replication.

6.2. Neural mechanisms in humans

To date, five functional MRI (fMRI) studies of SPS have been conducted in humans (Acevedo et al., 2014, 2017; Aron et al., 2010; Chen et al., 2011; Jagiellowicz et al., 2012), providing evidence for its neural basis (Fig. 3). Utilizing the HSP scale as a measure of SPS, two studies examined brain responses to perceptual tasks, while the other two investigated SPS responsivity to emotional stimuli. The fifth study examined differences in resting-state brain activity in association with SPS. Additionally, several behavioural studies of SPS have been conducted in humans, providing evidence that awareness of environmental subtleties and emotional reactivity is enhanced in SPS. Furthermore, while studies have not yet directly addressed depth of processing, empathy, and overstimulation, findings point towards differences in these also. These behavioural studies will be discussed in the context of the associated neuroimaging findings.

For one fMRI study examining perceptual responsivity as a function of SPS (Jagiellowicz et al., 2012), the study participants were scanned while doing a task to notice subtle differences in photographs of landscapes. Results showed that higher levels of SPS were associated with increased reaction times and increased activation of brain areas implicated in high-order visual processing and attention, such as the right claustrum, left occipito-temporal, bilateral temporal and medial and posterior parietal regions in response to detecting minor (versus major) changes in stimuli.

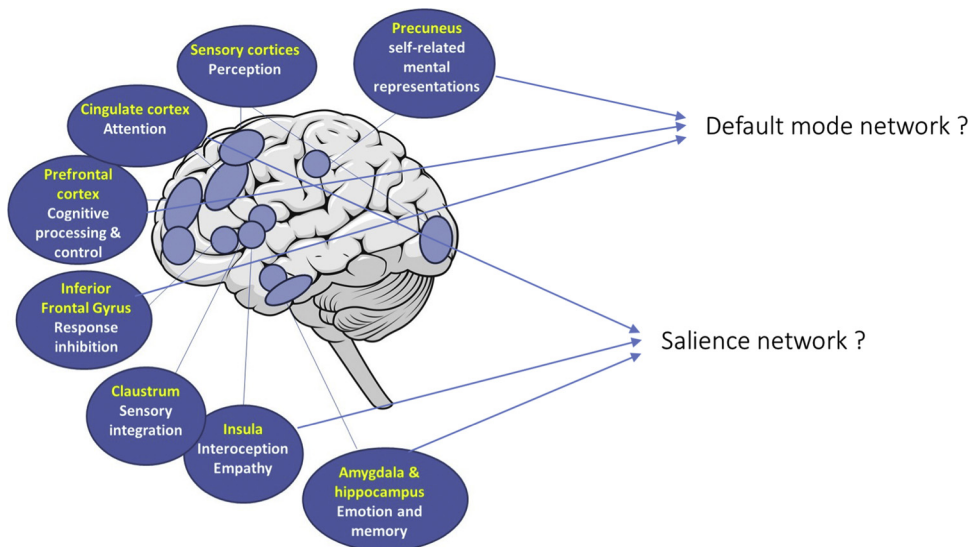


Fig. 3. Neural signature of SPS.

SPS is characterised by a 'hypersensitive' brain, reflected by heightened reactivity of the areas indicated in response to social-emotional or other environmental stimuli. Together, the activity patterns in the brain of high SPS individuals point towards deep information processing (e.g. precuneus, prefrontal cortex, inferior frontal gyrus), and increased emotionality and empathy (e.g. insula, claustrum, amygdala, cingulate cortex), the core facets that characterize SPS. Interestingly, these clusters of brain regions correspond to the default mode and salience networks, respectively, which mediate internal mentation and attention towards salient and emotional stimuli.

A behavioural study in a diverse sample of 97 adults likewise found that the high SPS group (top 30%) had higher reaction times to detect changes of an object in photographs only when the change is subtle (colour or size), not when more obvious (location, presence) (Bridges, 2018, unpublished doctoral dissertation; Bridges and Schendan, 2019b).

In another fMRI study examining the perceptual aspects of SPS using the HSP scale cross-culturally (Aron et al., 2010), Asians and Americans performed visuospatial tasks emphasising judgments that were already known to be either context-independent (typically easier for Americans) or context-dependent (typically easier for Asians), so that brain activation is generally higher when performing the more difficult task. It was found that individuals scoring high versus low on SPS showed lower culture-related differences in task performance. This suggests that SPS is associated with perceptual judgments that are based more directly on the actual incoming stimuli as they are, rather than on a cultural information 'filter'. In line, while the Asians and Americans displayed increased activation of the frontal and parietal cortices when performing the more difficult task, this was not found in the high SPS individuals among the Asians and Americans (Aron et al., 2010). These results are consistent with a behavioural study involving German undergraduate students which showed that SPS was positively correlated with enhanced performance in a visual detection task (Gerstenberg, 2012). Interestingly, though no neurobiological correlates were investigated, SPS has been explored in association with other visual stimuli and preferences and, specifically, it has been investigated whether it is associated with blur tolerance and high-chroma colors preferences. No significant association was identified between SPS and the degree of blur tolerance (Woods et al., 2010) nor with preferences for high-chroma colors, even though at a descriptive level individuals who are highly sensitive reported to like high-chroma colors less than individuals who were low on sensitivity (Woods et al., 2010).

In another fMRI study examining the neural correlates of SPS in response to emotionally evocative face images of a partner or stranger (Acevedo et al., 2014), recently married men and women were scanned twice (about one year apart). The task was specifically designed to measure empathic processes as participants were first prompted with a sentence describing the context of the face image with corresponding statements such as, "Your partner is feeling very happy because something wonderful has happened to them". The results revealed that across all conditions (and replicating across one-year), SPS (measured with the 11-item HSP scale) was significantly associated with increased activation in brain regions that coordinate attention and action planning (in the cingulate and premotor area). For happy and sad photo

conditions, SPS was associated with stronger activation in brain areas involved in sensory integration, awareness and empathy (insula and inferior frontal gyrus), as well as preparation for action and cognitive self-control (i.e., premotor area, cingulate, medial and dorsolateral prefrontal cortex). The insula is particularly interesting with respect to SPS because it is responsible for perceiving and integrating interoceptive sensory stimuli, and has been thought to be the "seat of awareness" (Craig, 2009). Also, activation of the inferior frontal gyrus was found, which is part of a Mirror Neuron System, a network of regions that are involved in empathic processing and facilitate rapid intuition of others' goals (Van Overwalle and Baetens, 2009). Similarly, the cingulate cortex is involved in attention and the recognition of others' actions (Rizzolatti et al., 1996). The premotor area finding is also of interest in the context of response to others' emotions as it is involved in unconscious behavioural control and action planning (Cross et al., 2006). Finally, the dorsolateral prefrontal cortex is involved in higher order cognitive processing, decision making, self-regulation and task performance (Dixon and Christoff, 2014). Accordingly, these data suggest that high SPS individuals may readily intuit, "feel" and integrate information, and respond to others' affective states, in particular to positive emotional states of a close partner (relative to a strangers', and to neutral affect). The results are consistent with cardinal traits of SPS as they highlight depth of processing, awareness and being more affected by others' moods and affective displays.

In another fMRI study of SPS (Acevedo et al., 2017), a group of females were scanned while viewing generally positive, negative, and neutral images from the standard International Affective Picture System – IAPS (Lang and Bradley, 2007). Participants also completed the HSP scale and provided retrospective reports of childhood quality, measured with a battery of validated scales. Results showed that SPS (and its interaction with a positive childhood environment) was significantly correlated with neural activity in areas involved in memory, emotion, hormonal balance, and reflective thinking (namely, the hippocampus, entorhinal area, hypothalamus, and temporal/parietal areas). Furthermore, results showed that SPS was associated with a stronger reward response (in the ventral tegmental area and nucleus accumbens) to positive stimuli; and this effect was especially amplified for individuals reporting higher quality childhoods. For negative stimuli, the SPS x childhood interaction showed significant activation in brain regions implicated in emotion-processing and self-regulation (i.e. the amygdala and prefrontal cortex), without diminished reward activity (which was seen for the simple correlation with SPS). These results provide a suggestion for how positive childhoods may have long-term impacts on individuals' susceptibility to stimuli, namely through mechanisms

related to self-regulation and by buffering individuals from dampened reward effects in response to negative stimuli.

Finally, researchers investigated whether resting-state brain activity mediated the effects of dopamine-related genes on SPS (Chen et al., 2011). It was found that temporal homogeneity of regional spontaneous activity in the precuneus suppressed the effect of dopamine-related genes on SPS. The precuneus is involved in the integration of higher-order information such as visuo-spatial imagery, episodic memory, and emotional stimuli, especially when self-related mental representations and self-processing are involved (Cavanna and Trimble, 2006; Ye et al., 2018). This finding indicates that the relation between SPS and dopamine genes is moderated by precuneus activity.

6.3. Neurocognitive mechanisms in humans

In two behavioural studies with English undergraduate students, high SPS groups were different on controlled and automatic attention tasks (Bridges, 2018, unpublished doctoral dissertation; Bridges and Schendan, 2019b). In one study using a standardized test, a high SPS or AES group made more errors only when the task involved incongruent flankers, supporting the association of SPS with greater attention to irrelevant information, which may promote greater depth of processing but can result in errors. In another study, high SPS individuals showed both more interference and more facilitation effects for spatial congruency on an automatic exogenous attention orienting task. Consistent with the idea that greater automatic attention may support greater awareness of subtle information, another behavioural study suggested that high SPS groups have a greater ability to become more consciously aware of subtle higher-order, structured information during an implicit learning task (Bridges, 2018, unpublished doctoral dissertation; Bridges and Schendan, 2019b). Neurosensitivity mechanisms, especially lower inhibition and automatic attention, may contribute to creative abilities in individuals high in SPS (Bridges and Schendan, 2019a, b). Altogether, these findings suggest that SPS is associated with differences in controlled and automatic attention neural processes that have implications for other aspects of cognition (e.g. memory, creativity), with some being beneficial and some not.

6.4. Animal models

Basic research on the neural and physiological mechanisms underlying SPS greatly advance our understanding of the construct. Since genetic evidence underlying personality traits, including SPS, is not yet conclusive, it is argued that basic research on the neural basis of behaviour in experimental animals is needed to further advance mechanistic understanding (Robbins, 2018). Indeed, animal models allow control over environmental factors as is not possible in humans, as well as invasive and causal manipulations. Thus, animal models may provide critical advances on the role of neuromodulators in behaviour and cognition in relation to biologically based traits. Sensitivity to environments is seen across many animal species, with two different behavioural patterns consistently reported: one bold, proactive and more extraverted; and another more cautious, reactive and inhibited (Pennisi, 2016; Wolf et al., 2008). Hence, using animal models to understand the biology underlying SPS is sensible.

One potential animal model that can help to advance the understanding of mechanisms is the serotonin transporter (5-HTT) knockout mouse/rat model. It is now widely accepted that these mouse and rat models modelling the 5-HTTLPR s-allele (Caspi et al., 2010; Homberg and Lesch, 2011) show behavioural resemblances with people who are high on SPS (Homberg et al., 2016). For instance, the knockout animals exhibit faster sensory processing (Miceli et al., 2017), show reduced latent inhibition (Nonkes et al., 2012) which is indicative for increased openness to (irrelevant) environmental subtleties (Carson et al., 2003), adapt better to changes in the environment (Nonkes et al., 2013), exhibit increased anxiety-related behaviour in response to novel or

emotionally conflicting situations (Kalueff et al., 2010), show increased responsivity to rewarding agents (Homberg et al., 2008; Nonkes et al., 2013), have a better memory for emotionally arousing events (Nonkes et al., 2012), and show depression-like phenotypes upon exposure to uncontrollable stress (Carola and Gross, 2011; Homberg and van den Hove, 2012). There is also evidence that 5-HTT knockout mice behave according to the *Differential Susceptibility* theory (Kaestner et al., 2015), as cohabitation of male mice with female mice reduced anxiety-like behaviour and increased exploratory locomotion in 5-HTT knockout but not control mice. Although the association between SPS and the serotonin system needs further replication (see Section 6.1), the phenotypic overlap encourages the use of 5-HTT rodents as a model for *Environmental Sensitivity* approximating SPS, in order to increase the understanding of the neural mechanisms underlying SPS (Homberg et al., 2016).

6.5. Excitation-inhibition balance

In line with the human fMRI studies, functional and structural imaging studies in 5-HTT rodents point to altered activity of the prefrontal cortex, amygdala, insula, nucleus accumbens, and hippocampus (Bearer et al., 2009; Pang et al., 2011; van der Marel et al., 2013). Brain activity responses as measured by fMRI reflect a summation of complex synaptic signalling events. Since information integration is dependent on balance between excitation and inhibition in the brain, mediated by the neurotransmitters glutamate and GABA, respectively (Tatti et al., 2017), the excitation-inhibition balance in the brain may well be the basis of the neural mechanisms driving increased sensitivity to environments. Using 5-HTT knockout rats as an animal model for *Environmental Sensitivity*, approximating high SPS (Homberg et al., 2016), it was found that faster sensory processing was associated with reduced inhibitory control over excitatory principal neurons in the somatosensory cortex, leading to increased excitability and sensory gating (Miceli et al., 2017). It is possible that the increased excitability extends to other regions beyond the somatosensory cortex, given that GABA system components are reduced in the somatosensory cortex, prefrontal cortex and hippocampus (Guidotti et al., 2012; Luoni et al., 2013; Miceli et al., 2017). Of interest, during brain maturation, GABA undergoes a switch from inducing depolarizing to hyperpolarizing responses in postsynaptic cells. This switch is dependent, amongst others, on increased expression of the K(+)/Cl(-) co-transporter (KCC2). In 5-HTT knockout rats, KCC2 expression is reduced in the cortex (Miceli et al., 2017), which would increase the membrane depolarization of postsynaptic cells receiving GABAergic inputs. This raises the possibility that the behavioural profile of 5-HTT knockout rats, and thereby *Environmental Sensitivity*, may relate to neuronal immaturity. As suggested by a group of neuroscientists, neuronal immaturity may be associated with increased plasticity and openness to the environment (Castrén, 2013).

6.6. Hypothalamus-pituitary-adrenal axis

Besides the brain, also related peripheral systems may contribute to sensitivity to environments. The hypothalamus-pituitary-adrenal (HPA)-axis is implicated in the bodily response to environmental insults, allowing the organism to respond in an adaptive manner. Studies using 5-HTT knockout rats revealed that under baseline conditions, plasma corticosterone levels are increased compared to wild-type rats, but reduced after moderate early life stress (Van der Doelen et al., 2014). This was related to increased adrenal mRNA levels of, e.g. the adrenocorticotrophic hormone (ACTH) receptor. With the use of an *in vitro* adrenal assay, naïve 5-HTT knockout rats were furthermore shown to display increased adrenal ACTH sensitivity. Interestingly, no changes in HPA-axis components were found in the hypothalamus and pituitary, suggesting that peripheral systems independent of the brain can contribute to sensitivity to environment.

It has been well-established that environmental factors have the ability to modify gene expression through epigenetic mechanisms. Epigenetic mechanisms refer to the changes in gene expression that do not involve changes in the DNA sequence. One type of epigenetic mechanism through which early life factors can alter gene expression later in life is DNA methylation, which involves the addition of methyl groups to the DNA, to convert cytosine to 5-methylcytosine. Highly methylated areas tend to be less transcriptionally active. Using 5-HTT knockout rats, it was found that DNA methylation of the corticotrophin releasing factor (CRF) was increased in the amygdala (but not the bed nucleus stria terminalis) of 5-HTT knockout rats exposed to early life stress, compared to wild-type control rats and rats not exposed to early life stress. This correlated significantly with reduced CRF mRNA levels. CRF mRNA levels were in turn found to correlate with improved stress coping behaviour, as a manifestation of sensitivity to environments (Van der Doelen et al., 2014). Thus, while no evidence was found for changes in HPA-axis components in the brain to regulate HPA-axis reactivity to early life stress (Van der Doelen et al., 2014), environmental factors may influence HPA-axis reactivity through epigenetic mechanisms in the brain.

6.7. Future directions

Research on the genetic and environmental aetiologies of SPS is still in its infancy. As candidate gene studies have been criticised for their reliance on a priori assumptions about the biological function of specific genes, which is limited at present (Assary, Vincent, Keers, and Pluess, 2017), a multi-pronged approach is needed to investigate the aetiology underlying SPS. Also, common and complex phenotypes, such as SPS, are expected to result from multiple genetic variants of small effect size (Flint and Munafò, 2013), as well as from synergistic interactions with the environment (Keers and Pluess, 2017).

To advance the understanding of the aetiology of SPS, we recommend different levels of analysis for future research. First, finding an association between SPS and 5-HTTLPR supports recent theoretical assumptions that high SPS and the s-allele share phenotypes, in terms of heightened sensitivity to environments and emotional reactivity (Homberg et al., 2016). Research with animals in the laboratory does suggest strong links between serotonergic gene variants and enhanced attention to emotional stimuli, a key feature of SPS (Homberg et al., 2016). Thus, it will be very relevant to conduct large scale studies examining serotonin gene variants in humans. Second, twin studies should be conducted in order to extend initial findings regarding the aetiologies of SPS beyond adolescents to children and adults, and to study stability and change over time of genetic and environmental effects. Further, twin-based DeFries-Fulker extremes analyses would be useful (Rende and Slomkowski, 2005), in order to assess whether high levels of SPS are quantitatively similar (aetiological continuity) or qualitatively different (aetiological discontinuity) from normal aetiological variation in SPS (Shakeshaft et al., 2015), further addressing the continuum vs category question from an aetiological standpoint (see also Section 4). Third, the genetic structure of SPS needs to be assessed in a GWAS of sufficient size, in order to develop a basic model for the specific genetic variants associated with SPS. Lastly, we recommend more novel molecular genetic approaches such genome-wide complex trait analyses and the identification of polygenic scores for SPS, which are created for individuals in a new target sample based on the number of trait-associated alleles weighted by their effect size from the discovery GWAS sample (Assary et al., 2017).

While the fMRI studies have brought substantial advances in understanding the neural underpinnings of SPS, this work is still in its infancy. One direction for future research we recommend is to examine large-scale brain networks. A paradigm shift in the field of cognitive neuroscience emphasises the functioning of the brain as an activity balance between sets of large-scale networks that support unique, broad domains of cognitive functions (Smith et al., 2009). These networks

include the salience network (Homberg et al., 2017; Sridharan et al., 2008) (key areas: insula and anterior cingulate cortex; bottom-up attention to salient stimuli and behavioural changes), and the default mode network (Gusnard et al., 2001) (key areas: ventromedial prefrontal cortex, rostral anterior cingulate cortex, precuneus; active when we are off task, mind-wandering, thoughts that are unrelated to the present sensory environment). Given the function of these networks, they may well underlie the SPS sensitivity facets. For instance, heightened emotional reactivity as observed in SPS could be related to increased salience network activity. Likewise, deep cognitive processing could relate to increased activity of the default mode network. Understanding the highly sensitive brain in terms of large-scale brain networks would significantly advance our insight in the neural basis of SPS. Specifically, it would help in understanding how deep information processing and heightened emotionality reactivity in SPS are associated with each other. An open question is whether deep cognitive processing is the central facet of SPS, and other phenotypes are secondary. It is also possible that reduced ‘filtering’ of sensory information, leading to increased awareness of environmental subtleties, drives subsequent increased emotional and cognitive processing of the sensory information. Specialised large-scale brain network analyses (e.g. dynamic causal modelling) allow the identification of a central node by investigation of directionality of functional connectivity between networks. Of interest to further understand the function of the high SPS brain is the Embodied Predictive Interoception Coding (EPIC) model. This model postulates that the brain anticipates incoming sensory inputs by generating predictions through past experiences. Detection of a salient stimulus by comparing the predictions to actual sensory input can then be used as an alerting/reorienting signal, and relayed to the appropriate nodes that can implement a shift in attention or behaviour (Barrett and Simmons, 2015). This process involves the generation of predictions by agranular cortices (e.g. insula, anterior cingulate cortex) and prediction errors by granular cortices in the salience and default mode network. Since large-scale brain networks have also been identified in rodents (Becerra et al., 2011; Huang et al., 2016; Kleckner et al., 2017; Lu et al., 2012; Sierakowiak et al., 2015), it represents an excellent translational assay, to link data derived from animal studies to humans.

While studies so far are compatible with the SPS characteristics of greater depth of processing and emotional reactivity, these characteristics have not been directly examined. In the brain perceptual information processing proceeds hierarchically from low to deep levels, that is, neurons coding low level features, such as lines, which converges onto the same neuron at a more advanced stage of processing to construct higher level features (Herzog and Clarke, 2014). Association cortex contains convergence-divergence zones wherein higher level information feeds back to lower levels, producing richer semantic representations embodied in lower level perceptual information (Meyer & Damasio, 2009). This raises the question of how depth of processing is related to perception. Evidence is accumulating that recurrent and top-down feedback processes in frontoparietal regions, which contribute to greater depth of processing, affect perception (Schendan and Ganis, 2015; Herzog and Clarke, 2014). Perception may be altered in SPS due to higher sensitivity of perceptual processing itself or to influences on perception from deeper information processing, including attention mechanisms, or top-down influences of high emotional reactivity. These possibilities may be distinguished using perceptual tasks (e.g. illusions, psychophysics), testing bottom-up versus top-down influences of neutral (e.g. using backward masking, or stimulus impoverishment (Schendan and Ganis (2015)). The use of empirical tests to assess sensory perception by itself may also reveal how SPS relates to changes in the perception of sensory information and deeper information processing. For instance, the ability to inhibit responses to incoming sensory information is an important feature of a healthy individual for which many conventional EEG tests are at hand such as sensory or sensorimotor gating. Indeed, in work prior to the definition of SPS, more creative people were found to be more sensitive, defined as habituating

more slowly to sensory noise (i.e. less ability to learn to filter out repeated irrelevant sensory stimuli) and higher skin potentials (Martindale et al., 1996). In line, 5-HTT knockout rats show reduced latent inhibition, also indicative for more attention for irrelevant sensory stimuli (Nonkes et al., 2012). Furthermore, creative people who are sensitive, defined as having high resting arousal, physiological over-reactivity to stimulation, and poor biofeedback performance, show more variable alpha EEG responses and -on tasks requiring more creativity- less blocking of alpha EEG (associated with perception and task anticipation and reflecting modulation of activity in sensorimotor, dorsal attention and default mode networks, Hacker et al., 2017; Capotosto et al., 2011; Martindale, 1977).

Notably, a field of human studies is emerging on the involvement of neuronal coherence and computation in gating and perception but also in other relevant cognitive functions such as multisensory integration, working memory, and selective attention (Wang, 2010), which may benefit SPS research. Depth of processing predicts differences in neurobehavioral characteristics of SPS in memory and attention reflecting greater semantic, elaborative, distinctive, and effortful information processing. For example, regarding memory, individuals high on SPS should perform better on episodic memory tests, which benefit from greater depth of processing. Consistent with this, groups with s- relative to l- allele of 5-HTTLPR and 5-HTT knockout rodents show higher episodic memory and attention (Roiser et al., 2006; Homberg and Lesch, 2011). Furthermore, high SPS individuals show higher episodic memory and more details, even following implicit learning, suggesting that automaticity of processes leads to better memory (Bridges, unpublished doctoral dissertation, 2018; Schendan, personal communication, 13 August 2018).

Finally, further investigation of physiological responses, like HPA-axis reactivity, are of interest to expand our understanding of the biology of *Environmental Sensitivity* and its objective measurement. Plasma ACTH and cortisol levels, and DNA methylation levels of genes related to the HPA-axis in blood cells, can readily be measured in humans, and these measurements can be extended to the brain in rodents. Of interest, 5-HTT knockout rats and human 5-HTTLPR s-allele carriers similarly display a decrease in heart rate in response to a threat predicting cue, and similarly show moderation of the heart rate response by a neural circuitry involving the amygdala and the periaqueductal gray (Schipper et al., 2019). Potential changes in autonomic regulation is supported by human imaging data whereby high SPS is associated with greater activation in the amygdala and PAG in response to emotionally evocative stimuli (Acevedo et al., 2017). While 5-HTT knockout rat data help to fine tune the understanding of mechanisms underlying high SPS, a drawback is that these rats are genetically defined, and not phenotypically like high SPS. Therefore, a phenotypic rat model based on extremes in emotionality and increased information processing in a population of wild-type rats is currently being developed. The phenotypes of this new phenotypic model resemble those of 5-HTT knockout rats, but the underlying aetiology is different. By combing animal and human research we can make significant advances in the mechanistic understanding of high SPS.

7. SPS, (mal)adaptive outcomes, psychopathology and intervention

7.1. Association of SPS with negative and positive outcomes

SPS is conceptualised as a trait rather than a disorder, but in interaction with negative environments high SPS may increase risk for maladaptation and negative developmental outcomes, including mental and physical symptoms (see also Section 8). Indeed, research has related SPS to a range of negative outcomes. These include higher levels of psychopathology-related traits, including internalising problems (Boterberg and Warreyn, 2016), anxiety (Bakker and Moulding, 2012; Jonsson et al., 2014; Liss et al., 2008; Meredith et al., 2016; Neal et al.,

2002), depression (Bakker and Moulding, 2012; Liss et al., 2008, 2005; Yano and Oishi, 2018), and traits of autism spectrum disorders (ASD) and alexithymia (Liss et al., 2008). SPS has also been associated with lower levels of subjective happiness (Sobocko and Zelenski, 2015), and lower levels of life satisfaction (Booth et al., 2015). It is also related to factors associated with poor stress management including difficulties in emotion regulation (Brindle et al., 2015), a greater but more accurate perception of home chaos (Wachs, 2013), increased levels of stress (Bakker and Moulding, 2012; Benham, 2006), physical symptoms of ill health (Benham, 2006), and greater work displeasure and need for recovery (Andresen et al., 2017; Evers et al., 2008). Interestingly, a computational based model has been proposed to try to get a better understanding on the association of SPS with feeling of distress and overwhelming, pointing out to the importance of an external regulator agent (a supportive person with normal sensitivity) to promote the ability of the highly sensitive one to gradually learn on his/her own on how to cope with upsetting stimuli. Recently, SPS has also been proposed as a trait associated with frequent nightmares and vivid images in dreams (Carr and Nielsen, 2017), a hypothesis that has yet to be tested, and has been reported to be higher in individuals with type 1 diabetes (Goldberg et al., 2018). Only part of these studies included interaction effects, but of those that did, most have supported the role of interaction with negative environments in predicting maladaptive outcomes, as reviewed in Section 2.2.

Central to the conceptualisation of SPS as reflecting sensitivity to environmental factors, is that SPS is not only relevant to understanding maladaptation, but also optimal development or even flourishing in positive environments. As such, higher levels of SPS have been related to positive outcomes, including increased positive affect following positive mood induction (Lionetti et al., 2018), increased social competence in interaction with positive parenting styles (Slagt et al., 2017), reduced depression scores and bullying and victimisation following intervention (Pluess and Boniwell, 2015; Nocentini et al., 2018), as reviewed in Section 2.2, and increased activation in the major reward centres of the brain in response to positive stimuli, such as smiling partner faces or generally positive emotional images (Acevedo et al., 2014) (Section 6.2), as well as higher creativity (Bridges and Schendan, 2019a, b). Further, the HSP scale correlates significantly ($r = 0.27$) with feelings of awe, which add to the pleasure and meaning in life, assessed using a standard 6-item Awe scale (Aron et al., 2018; Shiota et al., 2007). An association between SPS and higher creativity, determined by neurobiological factors, has been also proposed by other authors, at a theoretical level (Rizzo-Sierra, 2012; Rizzo-Sierra et al., 2012).

Regarding parenting, high SPS mothers are shown to score significantly higher on Parenting Difficulties (e.g. “Each day is full of hassles,” “I don’t get enough time to myself,” “I regret having become a parent”) and Attunement to Child (e.g. “I know what my child needs even before he lets me know,” “I stay calm with my child no matter what,” “One of my strengths is the creativity I bring to parenting”), whereas high SPS fathers scored significantly higher only on Attunement to Child (Aron et al., 2019). Results remained after controlling for external stressors, negative affectivity, education, marital status, age, and children’s age. Similar, a German study reported a negative association between transition to parenting and well-being in highly sensitive individuals (Schmuckle et al., 2017). Furthermore, in a sample of Chinese parents with children with ASD symptoms, SPS has been reported to negatively impact on parental mental health through an indirect effect on parental intolerance of uncertainty (Su et al., 2018). These findings suggest that for those high on SPS it is particularly important for their well-being to have ways to manage their perceived overstimulation of parenting, especially given that it could facilitate the expression of their self-reported benefit of the trait, their greater attunement to their children.

7.2. SPS in the context of psychiatry

SPS is linked to increased risk for atypical development and subsequent mental disorder symptoms (see also Section 7.1). Most work thus far has focused on links of SPS to symptoms of anxiety and depression in non-clinical samples. Borrowing from psychological models of depression, a recent theory explains the association between SPS and psychological distress (including depression and anxiety and somatic symptoms) as a secondary phenomenon of cognitive reactivity (i.e. maladaptive thought content and processes) to sensory information and related negative emotions (Bratholm Wyller et al., 2018). As such, it is not sensory stimuli per se or related negative emotions that are hypothesised to lead to psychological distress, but the secondary cognitive reactions of individuals to stimuli and emotions. This cognitive reactivity of individuals has been suggested to distinguish healthy and unhealthy individuals with high SPS (Bratholm Wyller et al., 2018). Such a model is trans-diagnostic as it explains psychological distress associated with SPS, independent of specific diagnoses. In support of this, Brindle et al. (2015) found that difficulties in emotion regulation partially mediate the link between SPS and depression. Further, Meyer et al. (2005) found that higher SPS is related to more negative cognitive and affective reactions to ambiguous social scenarios, which is a cognitive risk factor associated with anxiety and depression (Lau and Waters, 2017).

Next to anxiety and depression, sensitivity to environmental stimuli is also relevant to psychiatric disorders, such as ASD, attention-deficit/hyperactivity disorder (ADHD) and schizophrenia (Acevedo et al., 2018; Ghanizadeh, 2011). However, the relationships of SPS to these disorders remain to be clarified. Different links are possible, such as that SPS may act as a risk or protective factor, modifying factor (e.g. influence the symptom expression and treatment), precursor or endophenotype for different disorders, or as a cross-disorder (also trans-diagnostic) trait. Relevant to the question of similarities and differences to disorders involving sensory sensitivities, a recent review of the brain regions involved in each of the conditions revealed that SPS differs from ASD and schizophrenia in that in response to social and emotional stimuli, SPS uniquely engages brain regions involved in reward processing, empathy, physiological homeostasis, self-other processing, and awareness (Acevedo et al., 2018). However, no study has compared brain structure or function in high SPS individuals directly to those with disorders involving sensitivity to environments. Such studies are needed before more firm conclusions can be drawn.

A vibrant research area is the study of sensory symptoms in ASD, which have been added to the clinical symptoms of ASD in the DSM-5 (American Psychiatric Association, 2013). ASD is a neurodevelopmental disorder that is also associated with hypersensitivities (e.g. to smell, sound, touch), but unlike SPS it has also been linked to hyposensitivity (Marco et al., 2011), whereas hyposensitivity has neither been hypothesised nor examined for SPS. Yet, Jerome and Liss (2005), reported that individuals high in SPS experienced low registration, and postulated that this could reflect a compensatory mechanism put into place when an organism was so over-aroused that it shut down (see also Section 6). This mechanism has also been hypothesised to occur in individuals with autism (Gillingham, 2000). Research is needed to delineate whether low registration in SPS and hyposensitivity in ASD are related. Furthermore, it is unclear whether sensory sensitivities in individuals with ASD reflect basic sensory differences (e.g. sensitivity to discriminate between or detect sensory stimuli), or differences in affective response to these stimuli. No studies so far have quantified SPS among individuals with ASD or other diagnoses in order to test the extent of overlapping architectures of sensory processing. At the neural level, sensory symptoms are thought to originate from differences in low-level processing in sensory-dedicated regions in the brain of individuals with ASD (Robertson and Baron-Cohen, 2017), whereas SPS is associated with brain regions involved in reward processing, memory, physiological homeostasis, self-other processing, empathy and

awareness (Acevedo et al., 2018). This implies that sensory sensitivity has distinct qualities in ASD and SPS. More research is needed to understand whether and how sensory processing in ASD relates to SPS.

Lastly, there is a broad literature on sensory processing dysregulations including factors such as poor registration, sensitivity to stimuli, sensation seeking and sensation avoiding (Dunn, 1997). The relation of SPS to this literature needs further empirical testing. We reason that while individuals high in SPS may have any disorder, including Sensory Processing Disorder, the indications that nearly one third of the population may be high in SPS indicates that SPS is a not disorder (impairment). That is, it is unlikely that a disorder would be so prevalent under evolutionary pressure. Furthermore, the perceptual advantages of SPS, such as decreased influence of culturally induced perceptual biases (Section 6), would seem to suggest that SPS bestows perceptual processing advantages.

7.3. Intervention for high SPS individuals experiencing psychological distress

Individuals with high levels of SPS are shown to benefit more from psychological intervention (Nocentini et al., 2018; Pluess and Boniwell, 2015). Intervention approaches may therefore not only be particularly vital for individuals high in SPS, given the association of SPS with psychopathology and stress-related problems, but also particularly effective. Proposed interventions for individuals high in SPS experiencing psychological distress include those focusing on increasing an individual's self-efficacy regarding dealing with emotions (Brindle et al., 2015). Given that acceptance of negative affective states has been shown to partially mediate the association between SPS and symptoms of depression (Brindle et al., 2015), and given that associations between SPS and anxiety were only found when mindfulness and acceptance were low (Bakker and Moulding, 2012), mindfulness and acceptance-based programmes may also be valuable. Mindfulness-based interventions are increasingly shown to be effective in the reduction of stress, anxiety and depression relapse prevention (Khoury et al., 2013; Kuyken et al., 2016). Based on neuroimaging data showing greater responsivity to affective stimuli as a function of SPS in areas implicated in emotion (i.e. the amygdala), mindfulness-based trainings, and in fact different meditation types linked to deactivation of the amygdala (Acevedo et al., 2016), may be useful for the enhancement of self-control and diminished emotional reactivity in high SPS individuals (Acevedo et al., 2017).

A randomised-controlled study in 47 highly sensitive individuals, identified using the Orienting Sensitivity scale of the Adult Temperament Questionnaire, which is related to SPS (Evans and Rothbart, 2008), found that mindfulness-based stress reduction had large effects on stress, social anxiety, personal growth and self-acceptance, and moderate effects on emotional empathy and self-transcendence (Soons et al., 2010). Recently, it has been proposed that mindfulness-based cognitive therapy (MBCT) may ameliorate psychological distress in individuals with high levels of SPS through addressing cognitive reactivity, and that MBCT may have transdiagnostic intervention effects through mediation by cognitive reactivity of individuals high in SPS (Bratholm Wyller et al., 2018).

Recently, a computational based model has been proposed to try to get a better understanding on the association of SPS with feeling distress or overwhelmed, pointing to the importance of an external regulator agent (a supportive person with normal sensitivity) to promote the ability of the highly sensitive one to gradually learn on his/her own on how to cope with upsetting stimuli (Tran et al., 2018). Finally, a recent study involving Japanese students reported that physical exercise might moderate the association between SPS and depression tendencies in young adults, but the result has to be replicated in longitudinal studies to clarify the impact of physical activity on the association between sensitivity and depressive symptoms (Yano and Oishi, 2018).

7.4. Future directions

Most studies so far are based on non-representative (student) samples. Associations between SPS and mental disorder need to be quantified further, also in relation to clinical samples, longitudinal designs, mental health registries, objective and biological markers of physical health and stress (e.g. cortisol reactivity, inflammation, allergies), and economic impact of SPS in terms of expected occurred health-care costs.

An important line of future research is to examine the usefulness of SPS as a cross-disorder (or transdiagnostic) trait. Cross-disorder traits are not symptoms of disorder, but are, as neutral traits, uniquely suited to bridge psychiatric disorders with biological substrates of behaviour, clarify heterogeneity and comorbidity and inform cross-disorder interventions, not achieved by the current diagnostic systems (DSM: Diagnostic and Statistical Manual of Mental Disorders, ICD: International Classification of Diseases) (Rodríguez-Seijas et al., 2015; Walkup et al., 2017). SPS may be an ideal cross-disorder trait because it is: a) observed in humans and animals, b) heritable, and c) associated with traits of mental disorders. Furthermore, there is evidence supporting that aetiological factors involved in SPS (see Section 6.1) partially overlap with those in psychiatric disorders, for example serotonergic and dopaminergic genes are also involved in the aetiology of ADHD, anxiety and depression. SPS may be a suitable addition to the Research Domain Criteria (RDoC) (Insel, 2014), as the *Sensory Processing Sensitivity* framework has been established based on observing stimulus responsiveness in > 100 animal species (Aron et al., 2012), indicating a strong biological foundation. A logical progression is to use human neurocognitive measures, such as electro- or magneto-encephalography and event-related potential studies, in particular to expand this field to the human counterpart of cognitive neuroscience. A critical need is to characterize basic sensorimotor, perceptual, socio-emotional and neurocognitive function in relation to SPS, with learning and memory, attention, and emotional reactivity as the abilities that should vary most in SPS, but also other basic abilities (e.g. language, object and spatial processing, inhibition). Further, more complex abilities (e.g. meta-cognition, social perception and expression, deception, creativity) should be characterised, as differences in basic abilities will affect more complex ones, and widespread neurobehavioral differences, which may affect large-scale brain networks, are predicted based on the neural and developmental mechanisms of SPS. Such neurobehavioral characteristics will be important for defining what SPS is, developing objective measures of SPS in addition to questionnaires, and tracking neurobehavioral characteristics in SPS across the lifespan and as a function of different kinds of environments.

An unresolved question is to what extent SPS taps into the same construct of sensory reactivity as ASD. High SPS and ASD are both characterised by sensory sensitivities, but there are also important differences: SPS is a temperament trait and not a disorder, differs from ASD in terms of heritability (around 47% for SPS and 83% for ASD; Assary et al., 2019; Sandin et al., 2017), and higher empathy is expected in high SPS individuals (Aron et al., 2012), whereas certain aspects of empathy and social processing are often impaired in many individuals with ASD (Bons et al., 2013). Nonetheless, it is conceivable that children with high SPS are misdiagnosed for ASD for instance when they are exposed to negative environmental factors that precipitate social withdrawal. A crucial caveat is the extreme heterogeneity in symptom constellations and severity across the autistic spectrum. Many studies have addressed the relationship between “clinical” sensory symptoms (e.g. the Sensory Profile, an informant-rated scale used for ASD), often referred to as sensory modulation, and symptom severity and ASD subtype (Bruining et al., 2010; Bruining et al., 2014; Jeste and Geschwind, 2014). The construct of SPS opens up the interesting possibility to test the contribution of normal sensitivity to ASD morbidity. It has been postulated that many different aetiologies converge on final common pathways leading to ASD (Bourgeron, 2015; Cellot and Cherubini, 2014; Delorme et al., 2013). Differential sensitivity to the

environment might be an interesting factor to add to this list and explore via SPS-driven research.

SPS may be important for informing personalised intervention. Intervention effects may be greater and more long-term in those higher on SPS, as highly sensitive individuals process or internalise stimuli more deeply, which may allow them continuous application of the acquired intervention strategies. Research on the mechanisms (e.g. psychological, cognitive, genetic, neurobiological) underlying links between SPS and psychopathology, and the responsiveness of high SPS individuals to intervention will be important to help understand how interventions work and for developing new interventions derived from such mechanisms, with implications for more as well as less sensitive individuals. As SPS is both genetically and environmentally determined, it may be possible to target sensitivity to environments in less sensitive individuals in order to facilitate treatment effectiveness, for example by therapy affecting neurobiological substrate of SPS (e.g. through neurofeedback). As SPS appears to have consequences for predicting intervention success, measurement of SPS in clinical practice should be considered.

In addition to developing and testing effectiveness of interventions for individuals with high levels of SPS and psychological distress, there is also a need for prevention programmes for high SPS individuals to prevent them from shifting to atypical development and help them flourish, and to examine the conditions leading to psychological flourishing and positive health in individuals high in SPS (Huber et al., 2011; Seligman, 2011). A first step would be to educate individuals high on SPS about the trait, similar to psychoeducation programmes used in mental health settings (Montoya et al., 2011). These individuals can then be followed longitudinally to study the expected beneficial effects of being educated about the trait, either in relation to a control high SPS group not educated about their trait, or compared to the period before being informed. We expect that being aware of being high on SPS is key, as it allows to adopt appropriate self-care behaviours such as sometimes avoiding overstimulating situations and getting enough time to themselves to process their recent experiences. Another important step is to educate parents and teachers of children with high SPS about the trait, and to examine the effects of being raised and supported by parents and teachers who understand the child’s sensitivity on school performance, well-being and psychosocial adjustment.

8. Conclusion

With this review we have provided a comprehensive overview of the current status of research on SPS and knowledge gaps, and suggestions for future research. In Table 1 we have summarized the suggestions for future research in order to further understand SPS and to improve the management of mental health and well-being. While research on SPS is still in its infancy and there is need for greater methodological rigour of studies, there is now increasingly good evidence that SPS is distinct from other temperament and personality constructs. SPS allows measurement and mechanistic understanding of why some individuals are more sensitive to environmental influences than others. Since SPS is a basic individual characteristic also observed in animals it has far reaching implications. It provides the opportunity to explain individual differences in development in the context of environmental experiences, it may explain susceptibility to (stress-related) psychopathologies, and may allow early detection of individuals at risk and early intervention to prevent aberrant behavioural developments, and help high SPS individuals to flourish in modern society. We could envision a role for SPS in the Research Domain Criteria that describe behavioural domains across brain disorders (Insel, 2014). Specifically, its evolutionary roots provide the premise to obtain mechanistic understanding of SPS across species, and thereby to work towards its clinical implementation.

Table 1
Future research directions for SPS.

Topic	Future directions
SPS and other theories of <i>Environmental Sensitivity</i> Assessment of SPS	<ul style="list-style-type: none"> - Increase understanding about the core hypothesised features of SPS (see Fig. 1 and Section 6 for suggestions). - Develop more objective assessment of SPS alongside existing HSP and HSC scales, especially behaviour observational measures, and semi-structured interviews. - Further validate and optimise the existing HSP and HSC scales in terms of the ability to capture depth of processing, and current negative phrasing of the items. - Adapt the HSP/HSC scales to be invariant across countries.
SPS as a marker of <i>Environmental Sensitivity</i>	<ul style="list-style-type: none"> - Investigate the relationship between SPS and reactivity to tightly controlled manipulations of positive and negative environments.
SPS and other temperament/ personality traits	<ul style="list-style-type: none"> - Investigate SPS developmentally – are there windows of heightened responsivity to the environment? - Expand research consolidating the existing evidence for validity of the HSP/ HSC scales and independence from existing temperament and personality constructs.
SPS: Category or continuum?	<ul style="list-style-type: none"> - Analyse SPS in terms of facets of Five Factor Model personality domains. - Examine the taxonic or dimensional nature of the SPS construct, especially by conducting state-of-the-art taxometric analyses which have particular strength to answer this question
Biological basis of SPS	<ul style="list-style-type: none"> - Conduct longitudinal twin studies, across developmental ages. Conduct twin-based DeFries-Fulker extremes analysis of HSP/HSC scale to address the question of genetic (dis)continuity. - Conduct molecular genetic analyses of SPS, especially GWAS and polygenic risk scores. - Extend human and animal fMRI studies towards large-scale brain networks. - Elucidate whether SPS is related to changes in physiological responses, as assessed by galvanic skin responses, heart rate variability, and basal and stress-induced glucocorticoids levels. - Assess the epigenetic mechanisms underlying SPS x environment interactions.
SPS, psychopathology and intervention	<ul style="list-style-type: none"> - Conduct studies relating SPS to more rigorous assessments of mental health and well-being (e.g. multi-informant, interview-based), and to objective and biological markers of physical health and stress (e.g. cortisol reactivity, inflammation, allergies etc.). - Obtain more mechanistic insight in how high SPS relates to and differs from mental disorders including sensitivity to environment. - Take into account SPS in explaining treatment heterogeneity. Study mechanisms underlying SPS as a predictor of treatment response, to help to design new intervention strategies for sensitive and less sensitive individuals. - Develop and study the effectiveness of prevention and positive intervention programmes for high SPS individuals.

Note: HSP = Highly Sensitive Person; HSC = Highly Sensitive Child.

Declarations of interest

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